Ultra-low noise microwave photonic oscillator using free running Kerr soliton microcomb with inhibited Raman scattering and dispersive wave emission

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Abstract: We demonstrate that K-band microwave with ultra-low phase noise (-60dBc/Hz@10Hz; -110dBc/Hz@1kHz; -140dBc/Hz@100kHz) can be generated by photo-detecting the repetition rate of a soliton microcomb with largely restricted Raman scattering and dispersive wave emission.

1. Introduction

Dissipative Kerr soliton optical frequency comb (soliton microcomb for short) generated in optical micro-cavity has been recognized as a promising technology to make the conventionally complex, expensive and large-volume optical frequency comb (OFC) system into a portable or even chip-integrated device, thus to bring OFC to more widely spread applications. One possible and highly useful functionality of soliton microcomb is to generate ultra-stable microwaves by photo-detecting the repetition rate of the soliton pulse train circulating within the micro-cavity (i.e., microcomb line spacing) [1-6]. Table I summarizes the performances of prior reported soliton microcomb photonic oscillator, it is seen that low phase noise microwave signals have already been generated in different microcomb platforms, some of which are already comparable with the specifications of best electrical oscillators. Nevertheless, a few physical effects, well known but yet to be solved, still constrain the noise performance of soliton microcomb as a microwave oscillator.

Table 1. Summary of the phase noise performances of different soliton microcomb photonic oscillators

			Phase noise (dBc/Hz, scaled to 21.5 GHz)		
Material	**Configuration**	**Carrier freq. (GHz)**	**1kHz**	**100kHz**	**Ref.#**
Si_3N_4	Free running pump+ quiet point	19.6	-81	-131	[1]
MgF_2	Self-injection locked pump	9.9	-113	-125	[2]
MgF_2	USL pump + PHD locked cavity + ν_{rep} injection + quite point + OFD	14.1	-117	-151	[3]
SiO_2	PDH locked pump+ quiet point	15.2	-87	-137	[4]
SiO_2	Brillouin laser pump	10.43	-82	-140	[5]
SiO_2	Free running auxiliary laser heating	21.5	-110	-140	this work

Equation 1 shown below express the dependence of soliton repetition rate ν_{rep} of a microcomb on the parameters of the micro-cavity and the pump laser [1, 4]:

$$\nu_{\mathrm{rep}} = \frac{1}{2\pi}\left[D_1 + \frac{D_2}{D_1}(\Omega_{\mathrm{Raman}} + \Omega_{\mathrm{Recoil}})\right] + \Delta\nu_{\mathrm{pp}} + \Delta\nu_{\mathrm{Q}} \tag{1}$$

Here, D_1 is the spectral range (FSR) and D_2 is the dispersion coefficient of the micro-cavity. Ω_R is quantity of Raman induced soliton self-frequency shift (SSFS), and Ω_{Recoil} is the dispersive-wave induced frequency recoil of the soliton microcomb spectrum. $\Delta\nu_{pp}$ denotes the variation of soliton repetition rate due to pump laser intensity noise, and $\Delta\nu_Q$ denotes the quantum-limited soliton time jitter. As has been studied in prior literature, the random fluctuations of the soliton repetition rate ν_{rep} primarily come from the factors Ω_{Raman} and Ω_{Recoil}, which can be further expressed as [3, 4]:

$$\Omega_{\mathrm{Raman}} = -\frac{8D_2\tau_R Q}{15\omega_0 D_1^2}\frac{1}{\tau_s^4} \tag{2}$$

$$\Omega_{\mathrm{Recoil}} \propto \frac{1}{(\Delta\omega')\left[(\Delta\omega_{\mathrm{r}}-\Delta\omega')+\frac{\kappa_{\mathrm{B}}^2}{4}\right]} \tag{3}$$

In Equation 2, Q is the quality factor, and τ_R the Raman time constant of the micro-cavity, ω_0 is the pump laser angular frequency, τ_s is the soliton pulse width. In Equation 3, $\Delta\omega'$ denotes the frequency difference between the soliton resident cavity mode and the dispersive-wave resident cavity mode, $\Delta\omega_r$ denotes the detuning of the r-th microcomb line, and κ_B denotes the decay rate of the dispersive-wave mode. Current wisdom to stabilize the soliton repetition rate ν_{rep} and minimize the phase noise of the photonic microwave oscillator is to let Ω_{Raman} and Ω_{Recoil} balance out each other (not to care about their absolute values), so that the soliton microcomb works in a 'quiet point' with near-zero slope in the ν_{rep}-versus-ω_0 curve. However, this scheme usually suffers from the limited existence range of the 'quiet point', and moreover, the effect of dispersive-wave emission and the associated factor Ω_{Recoil} is based on avoided mode crossings between different cavity mode families, which is usually hard to deterministically access during the fabrication of micro-cavities. Here, we demonstrate that ν_{rep} can be, alternatively, stabilized by minimizing the absolute quantities of Ω_{Raman} and Ω_{Recoil}.

2. Experiment and results

Our experiment utilizes a SiO_2 whispering-gallery mode (WGM) micro-rod cavity fabricated via CO_2-laser machining, as shown in Fig. 1a. Using the optimizing fabrication process, our micro-cavity exhibits excellent characterizations: FSR ~21.5 GHz, sparse mode distribution (see Fig. 1b), loaded Q-factor approaching 1 billion (see Fig. 1c). For soliton microcomb generation in the WGM micro-cavity, the method of auxiliary laser heating is adopted to bypass nonlinear thermal dynamics of the micro-cavity (see Fig. 1d) [6], the powers for the auxiliary and pump laser are set to 16 mW and 5 mW, respectively. The generated soliton microcomb spectrum is shown in Fig. 1e.

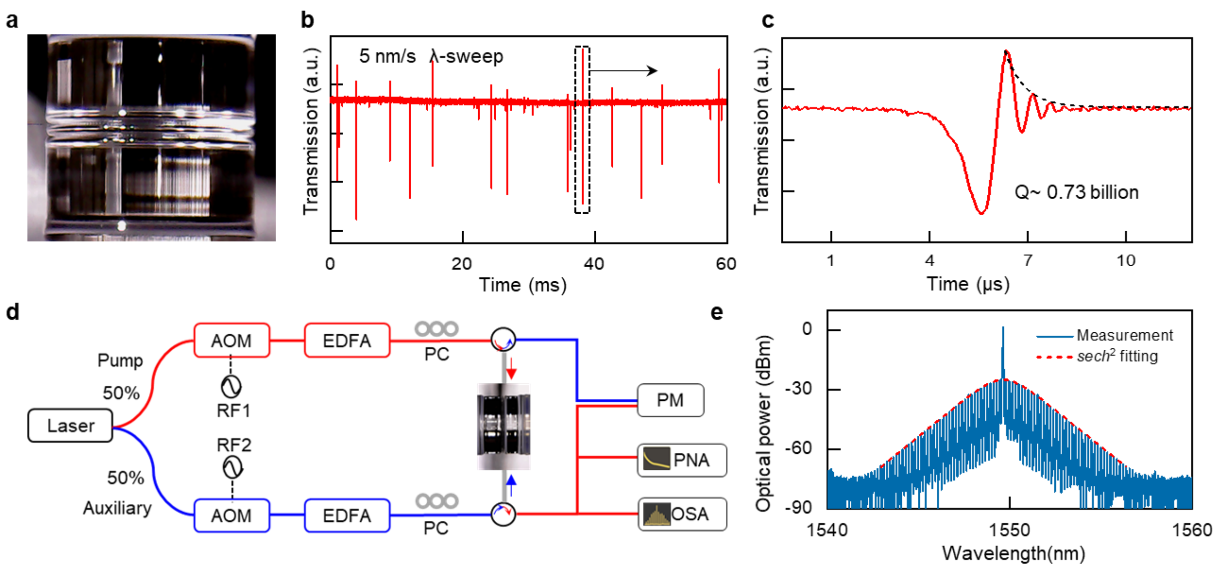

Fig. 1. a. WGM micro-rod picture. b. micro-cavity transmission and c. Ring down measurement of the pump cavity mode. d. Experimental setup. e. Generated soliton microcomb spectrum.

First, it is seen from Fig. 1e that the soliton microcomb spectrum is perfectly smooth, without any sizable dispersive waves or suppressed comb lines due to avoided mode crossing. This feature originates from the small mode density of our WGM micro-cavity (see Fig. 1b), as well as the relatively small spectrum bandwidth (20 dB bandwidth 6.88 nm, *sech*^{2} fitting) of the generated soliton microcomb. Such small soliton band-width is caused by the large mode area and concomitant small nonlinear coefficient (γ~10^{-3}) of our SiO_2 WGM micro-rod cavity. Thus, we can speculate that Ω_{Recoil} should be negligibly small for our microcomb.

Second and equally important, it is seen from Fig. 1e that the center of the generated soliton spectrum aligns well with the pump laser, indicating that Raman-induced SSFS has been heavily suppressed in our micro-cavity. Such phenomenon can also be interpreted by the small spectrum bandwidth of the microcomb, which corresponding to a transform limited soliton pulse temporal width (τ_s) of ~1.0 ps. According to Equation 2, the Raman-induced SSFS factor Ω_{Raman} depends on τ_s^{-4}, therefore, small soliton pulse width leads to substantial constrain of the factor Ω_{Raman}.

For example, our soliton spectrum bandwidth is about a quarter of the soliton generated in [4] (pulse width is approximately 4 times wider), and correspondingly our Ω_{Raman} is in principle ~250 times smaller.

Third, as detailed in our prior study [6], the method of auxiliary laser heating let the micro-cavity hold self-thermal locking even when the pump laser enters the red-detuning regime to access soliton state, which in effect stabilize the pump detuning $\delta_\omega=\omega_0-\omega_c$ and suppress the variation of soliton pulse width τ_s caused by the random drift of pump laser frequency. In fact, in our setup the auxiliary laser and pump laser are derived from the same laser module, and their frequency interval is highly stable (determined by the driving signals to the AOMs in Fig. 1d). Such configuration can bring about further stabilization of the pump detuning δ_ω via the combinational effects of thermal and Kerr cross-phase modulation between the auxiliary and pump lasers, this phenomenon will be elaborated in our presentation.

With the above phenomena, we can speculate that the repetition rate ν_{rep} of our soliton microcomb should be highly stable, and by sending the microcomb into a fast photodiode, the generated microwave signal will have ultra-low phase noise. The experimental measured phase noise of the ~21.5 GHz ν_{rep} of our soliton microcomb is shown in Fig. 2, and the sampled phase noise values at typical offset frequencies are listed in Table I for comparison. It is seen that the ν_{rep} in our experiment is indeed of quite stable, the generate microwave phase noise is excellent. Although the residual noise of the AOMs in our setup causes a few spurs (as presented in Fig. 2, which can be eliminated by optimizing the driving of AOMs), our phase noise result is already considerably better than most prior reports. E.g., when compared with the SiO_2 soliton microcomb operating in the quiet-point regime as reported in [4], the phase noise obtained in our experiment is 15 dB smaller at 10 Hz offset, and 23 dB smaller at 1 kHz offset. Moreover, our result also surpasses the phase noise performance of soliton microcomb generated by intra-cavity Brillouin pump laser [5] or self-injected pump laser [2]. Of note, literature [3] reported better phase noise than our result shown in Fig. 2, but quite sophisticated feedback stabilization techniques were used in [3], including ultra-stable pump laser, Pound-Drever-Hall locking of the micro-cavity resonance, injection locking of the soliton repetition rate, and optical frequency division. In comparison, our demonstration only uses free running pump laser and a stand-alone micro-cavity in the ambient environment, such assembly of high-performance and simplicity highlights the validity of stabilizing soliton microcomb ν_{rep} by restricting the Raman scattering and dispersive wave emission.

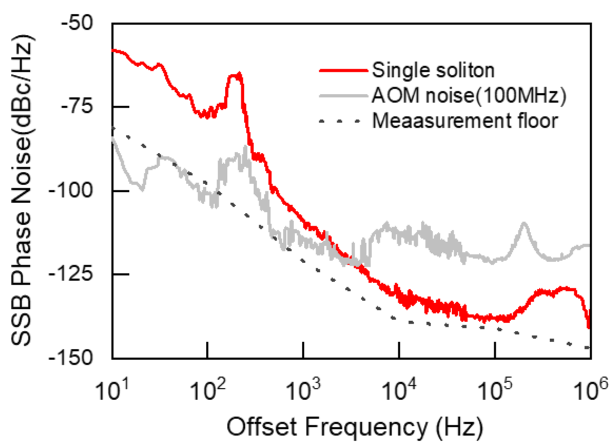

Fig. 2. SSB phase noise of the 21.5 GHz microwave generated by photo-detecting ν_{rep}.

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3. References

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